Hybrid turbulence models for atmospheric flow
A proper comparison with RANS models

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Current issues in atmospheric modeling

- Computationally expensive if accuracy is needed
  - **Possible solution :** Hybrid models
- Turbulence theory is mainly based on flat terrain studies
  - i.e. wall-functions are used in complex terrain
  - **Possible solution :** A different approach for wall treatment in ABL

Proposed turbulence model :

$k - \omega$ SST-SIDDES

(Simplified Improved Delayed Detached-Eddy Simulation)

Objectives

Main research objective :

Thorough validation of the proposed model for use in complex terrain

SOWE 2014 objective :

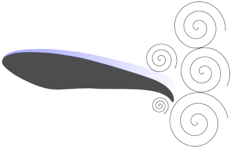
Validation cases : -Atmospheric surface-layer*
-Atmospheric boundary-layer*

*Flat rough terrain, neutral stratification and no Coriolis effects

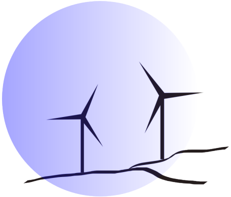
Focusing on comparing with a RANS model

Detached eddy simulation

- **DES :** hybrid model developed for massively separated flows
  - **URANS** to solve the boundary layer
  - **LES** outside the boundary layer



- **but** only the boundary layer is important for atmospheric flows
  - wall-modeled LES $\rightarrow$ **SIDDES** approach is needed



Proposed turbulence model

$k - \omega$ SST-SIDDES (Gritskevich et al., 2012)

- Hybrid approach based on :
  - SIDDES
  - RANS $k - \omega$ SST (Menter et al., 2003)
    - Good results for adverse pressure gradient and separation regions, and its roughness treatment

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\right]$$

URANS-mode : $\overline{u}_i$ is the time-average velocity

LES-mode : $\overline{u}_i$ is the filtered velocity

$k-\omega$ SST-SIDDES

$$\frac{\partial k}{\partial t} + ... = \tilde{P} - \underbrace{\frac{k^{3/2}}{\tilde{l}}}_{\epsilon}$$

$$\frac{\partial \omega}{\partial t} + ..$$

In the URANS-mode and LES-mode :

$$\nu_t = \frac{a_1 k}{\max(a_1 \omega, \mathcal{S} F_2)}$$

The length scale $\tilde{l}$ will determine the "mode" of the equations locally and varying in time

Length scale definition

Detached Eddy Simulation (DES) (Spalart et al., 1997)

$$\tilde{l}_{DES} \equiv min(l_{RANS}, l_{LES})$$

**Might yield erroneous results for ABL flows

Simplified Improved Delayed Detached Eddy Simulation (SIDDES) (Gritskevich et al., 2012)

$$\tilde{l}_{SIDDES} \equiv \tilde{f}_d l_{RANS} + (1 - \tilde{f}_d) l_{LES}$$

Roughness treatment

- $k - \omega$ SST can be integrated down to the wall
  - wall-functions can be avoided

- The surface roughness is generally accounted by
  - a modification of the original equations
  - or a wall-function

$k - \omega$ SST accounts for roughness simply through the boundary conditions of k and ω

Roughness extension (Knopp et al., 2009)

- For fully rough surfaces :

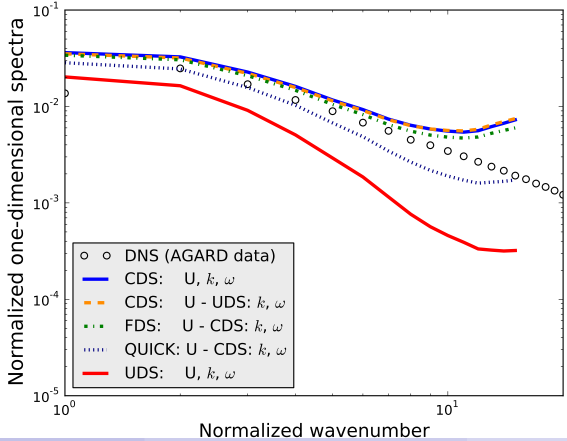
$$k|_{w,ABL} = \frac{u_*^2}{\sqrt{\beta_*}} \qquad \omega|_{w,ABL} = \frac{u_*}{\sqrt{\beta_*}\kappa z_0}$$

$$u_*^2 = (\nu + \nu_t)\frac{\partial u}{\partial n}\Big|_w$$

- A proper mesh is needed $\rightarrow$ $z_1^+ \approx 0.3$
  - $z_1^+ \approx 10^4$ for practical ABL grids $\rightarrow$ Can be costly !
  - Extremely elongated cells close to the wall
    - The *blockMesh* was the main challenge

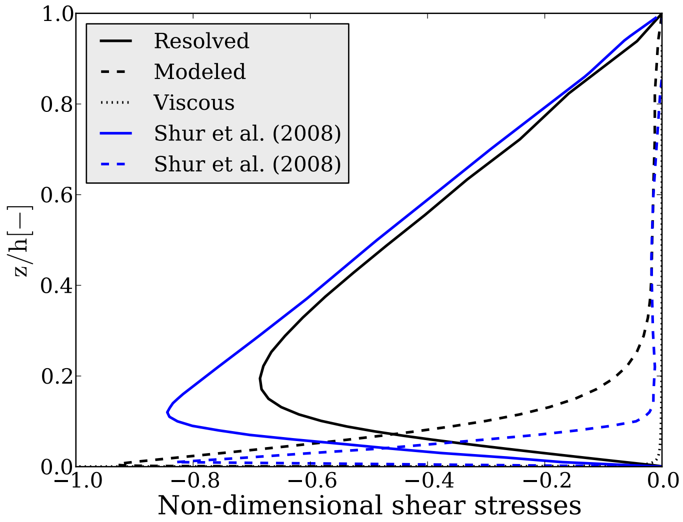
Discretization schemes

- Recommended schemes :
  - **RANS :** upwind (for stability)
  - **LES :** central difference (to reduce numerical dissipation)
- Decaying isotropic turbulence test-case (LES-mode) :



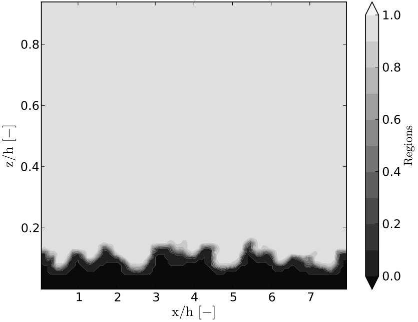
Discretization schemes

- Smooth channel flow using central difference (URANS and LES) :

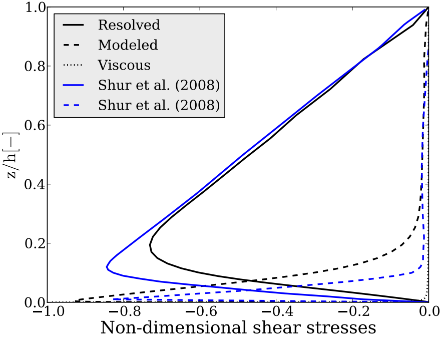


Blended discretization schemes

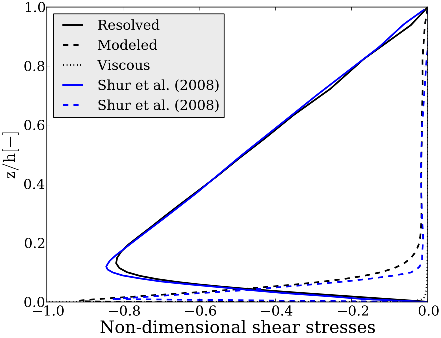
- Blended schemes based on the instantaneous URANS/LES regions
  - **LES** (light-gray) : 2nd CDS
  - **URANS** (black) : 2nd UDS



Blended discretization schemes



Blended schemes : U, k and ω



Central schemes : U
Blended schemes : k and ω

How to compare RANS and hybrid simulations ?

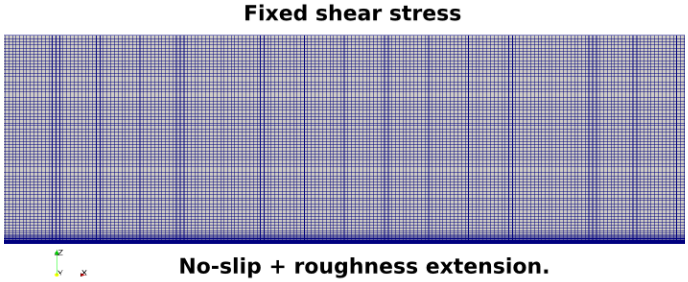
Atmospheric surface layer (ASL)

- Monin-Obukhov theory is valid throughout the domain
  - Logarithmic velocity profile, constant tke, ...
- The height of the ASL is fixed
- Relevant case (?) :
  - historical reasons
  - more control over the incident flow on wake studies (Jimenez et al. 2010)

Case 1 : modeling the ASL

- **RANS :** Fixed shear stress at the top boundary
- **LES/hybrids :** Imposing a fixed shear stress is not as evident and some undesired phenomena may occur

Case 1 : Atmospheric surface layer



- Periodic : streamwise and spanwise
- RANS : steady $k - \omega$ SST
- Hybrid : unsteady and taller domain (to account for the buffer layer)
- $z^+ \sim 1$ with a stretching up to 100 m, then uniform $\Delta = 15$ m

How to impose a constant shear stress ?

The value of the wall shear stress,

$$\tau_0 = \rho u_*^2$$

is imposed at the top boundary :

$$\tau_{top} = \rho u_*^2$$

$$\tau_{total} = \tau_{viscous} + \tau_{modeled} + \tau_{resolved}$$

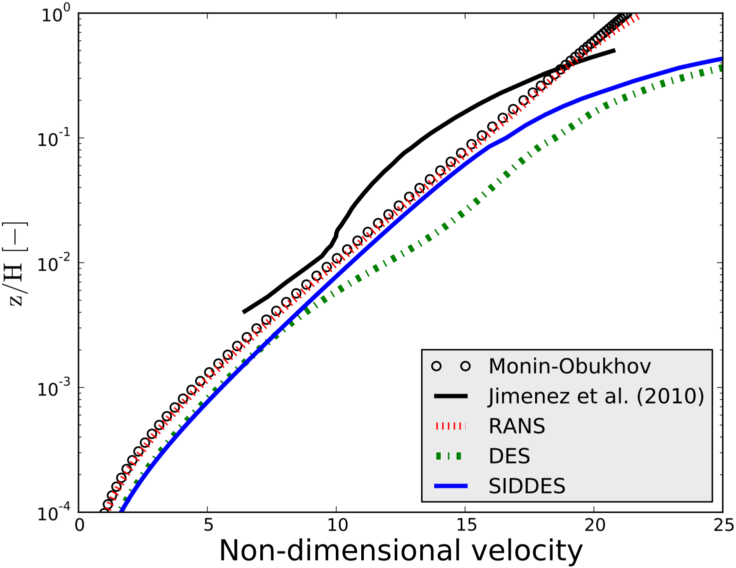
RANS :

$$\tau_{total} \approx \rho \nu_t \frac{\partial \bar{u}}{\partial z}$$

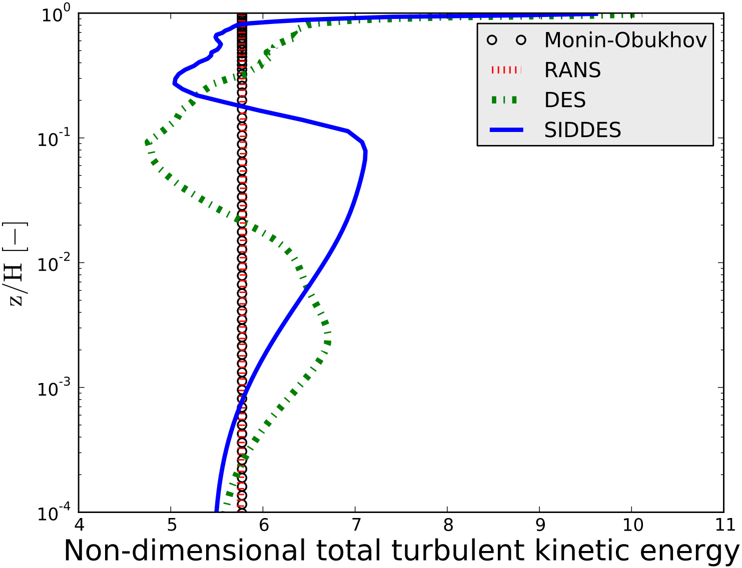
LES :

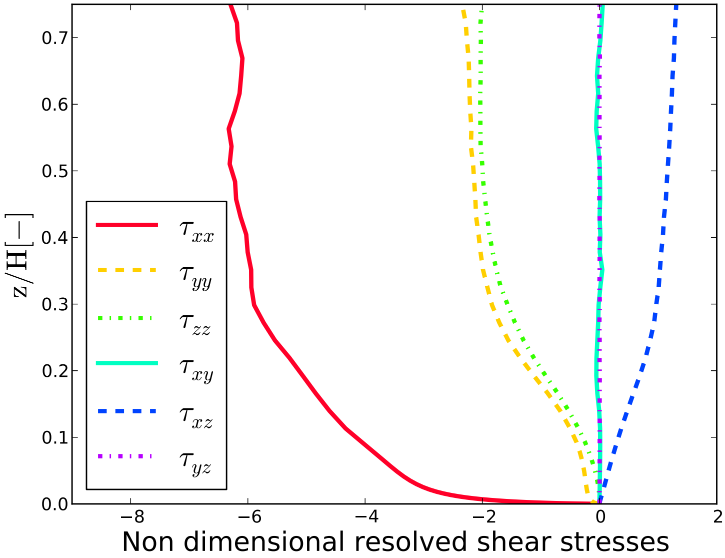
$$\tau_{total} \approx \rho \nu_t \frac{\partial \bar{u}}{\partial z} - \rho \langle \bar{u}' \bar{w}' \rangle$$

Case 1 : ASL results



Case 1 : ASL results





0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
z/H[−]
−8
−6
−4
−2
0
2
Non dimensional resolved shear stresses
τ_{xx}
τ_{yy}
τ_{zz}
τ_{xy}
τ_{xz}
τ_{yz}

How to compare RANS and hybrid simulations ?

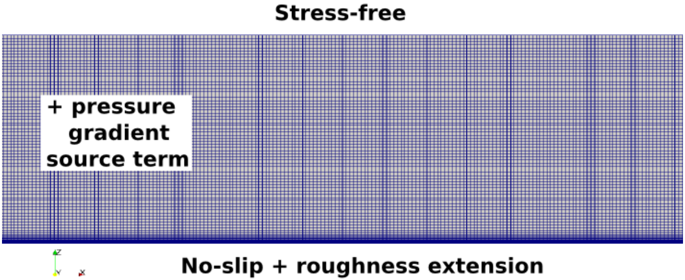
Atmospheric boundary layer (ABL)

- Monin-Obukhov is only valid in $\sim$10-20% of the domain
- It might be more representative of what happens in reality.

Case 2 : modeling the ABL

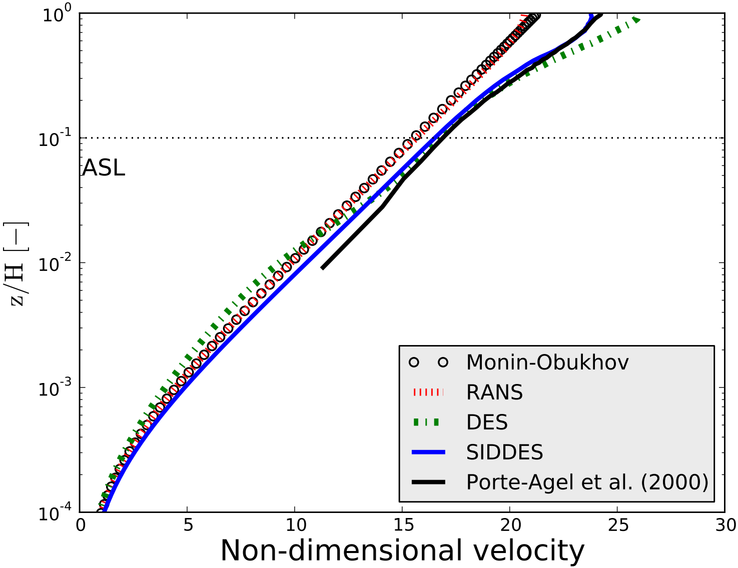
- **RANS :** Introducing a length-scale delimiter (i.e. eddy-viscosity models)
- **LES/hybrids :** Flow is driven by a pressure gradient source term

Case 2 : Atmospheric boundary-layer

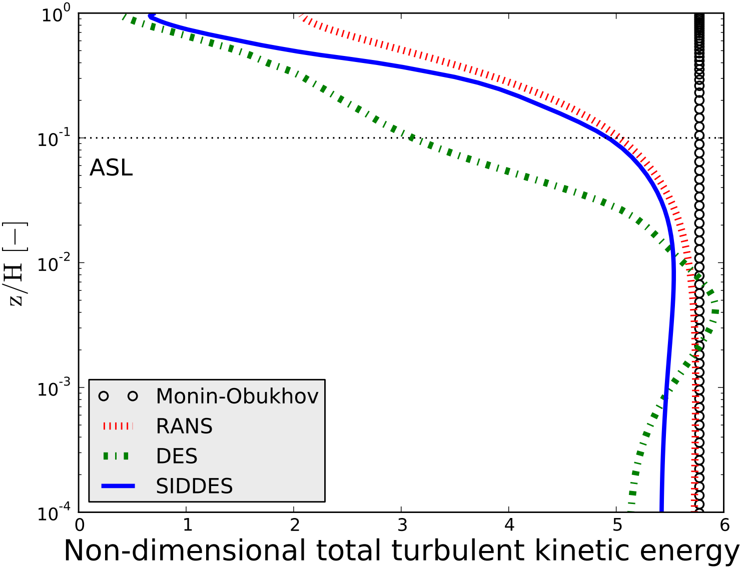


- Periodic : streamwise and spanwise
- RANS : steady and no length-scale delimiter
- $z^+ \sim 1$ with a stretching up to 100 m, then uniform $\Delta = 15$ m

Case 2 : ABL results



Case 2 : ABL results



Conclusion

The $k-\omega$ SST-SIDDES :

- could provide a good compromise between accuracy and computational cost
- avoids the use of wall functions

The flat terrain analysis :

- is crucial to understand the model and its limitation
- is not based on “flat terrain assumptions”

Conclusion

A simple comparison between RANS and the mean values obtained in hybrid simulations prove to be not really straight forward.

Atmospheric surface-layer validation case

- Imposing a shear stress did not yield acceptable results for the hybrid models :
  - velocity profiles are not correct
  - but the shear stresses are constant

Atmospheric boundary-layer validation case

- SIDDES gives more accurate results than DES
- Further analysis is needed to compare the hybrid simulations to RANS. (i.e. include length-scale delimiter)
- A more complete grid analysis might be needed, including Brasseur and Wei (2010) criteria to avoid a possible “overshoot”.

Thank you !

Questions ?

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